

# Rare Top Quark Decays at the LHC

J. Ferrando

University of Oxford

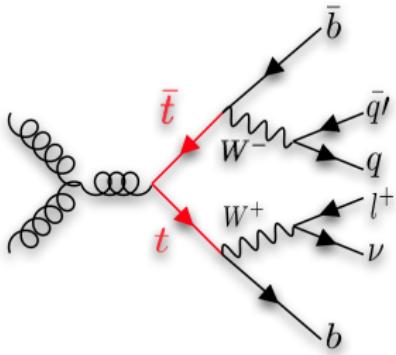
Blois 2010  
on behalf of:



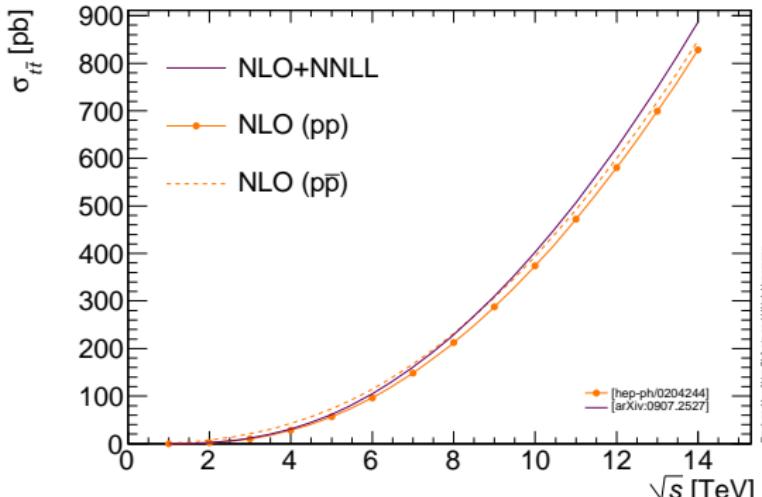
- 1** Introduction
- 2** Rare decays via charged currents
- 3** Rare decays via flavour changing neutral currents
- 4** Summary



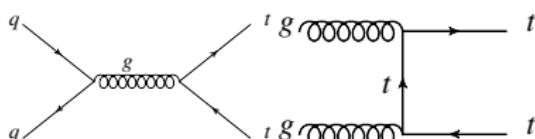
# Top production @ the LHC



- SM cross section of  $\mathcal{O}(200 \text{ pb})$  @7 TeV for  $t\bar{t}$  production at the LHC
- 10s of thousands of tops in  $100 \text{ pb}^{-1}$



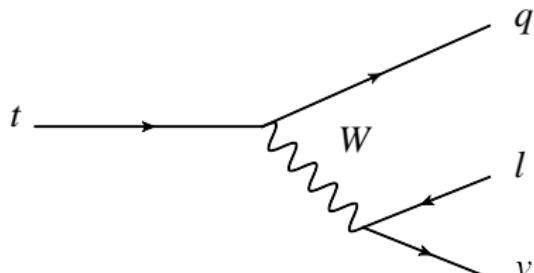
Produced by Alireza Shabani and Ulrich Haischmann



An ideal location to study the decays of top quarks!



# Rare Top Decays



In the SM the top decays  $t \rightarrow bW$  with branching fraction  $\sim 1$

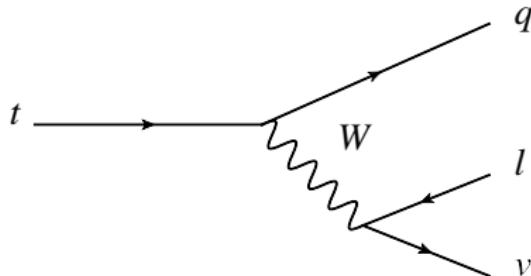
## From the 2009 Review of Particle Physics:

$$V_{\text{CKM}} = \begin{pmatrix} 0.97419 \pm 0.00022 & 0.2257 \pm 0.0010 & 0.00359 \pm 0.00016 \\ 0.2256 \pm 0.0010 & 0.97334 \pm 0.00023 & 0.0415^{+0.0010}_{-0.0011} \\ 0.00874^{+0.00026}_{-0.00037} & 0.0407 \pm 0.0010 & 0.999133^{+0.000044}_{-0.000043} \end{pmatrix}$$

(Assumes unitarity, 3 quark generations)

- Very few  $t \rightarrow Ws$ ,  $t \rightarrow Wd$
  - No  $t \rightarrow Zq$ ,  $t \rightarrow \gamma q$  (at LO, higher orders GIM suppressed)





It is very challenging to measure  $BR(t \rightarrow Wd)$  or  $BR(t \rightarrow Ws)$  directly. In early data, more straightforward to measure:

$$R = \frac{BR(t \rightarrow Wb)}{BR(t \rightarrow Wq)}$$

giving sensitivity to the  $Wd, s$  channels and a constraint on  $|V_{tb}|$ :

$$R \approx \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} = |V_{tb}|^2 \text{ (for 3 } q \text{ generations)}$$

CDF<sup>1</sup> and D0<sup>2</sup>:  $R > 0.61$  and  $R > 0.79$  respectively (95% C.L.).

<sup>1</sup>Phys.Rev.Lett.95:102002 (2005)  $\rightarrow |V_{tb}| > 0.78$

<sup>2</sup>Phys.Rev.Lett.100:192003 (2008)  $\rightarrow |V_{tb}| > 0.89$



CMS have performed feasibility studies for the measurement of  $R$  at  $\sqrt{s} = 10$  TeV with:



- dileptonic  $t\bar{t}$  ( $e\mu$ ),  $250 \text{ pb}^{-1}$ : CMS PAS TOP-09-001
- semi-leptonic  $t\bar{t}$ ,  $1 \text{ fb}^{-1}$ : CMS PAS TOP-09-007

Both approaches use the number of  $b$ -tagged jets. Probability of having a number  $k$  of  $b$ -tagged jets,  $P_k$  can be written:

$$P_k(R, \epsilon_b, \epsilon_q) = R^2 P_k(bb) + 2R(1 - R)P_k(bq') + (1 - R)^2 P_k(q'q')$$

for dileptonic events, or:

$$\begin{aligned} P_k(R, B, M) &= R^2 P_k(bWbW) + 2R(1 - R)P_k(bWq'W) \\ &\quad +(1 - R)^2 P_k(q'Wq'W) \end{aligned}$$

for semileptonic events.  $q' = d$  or  $s$ ;  $M$  or  $\epsilon_q$  is the mistagging rate.  $B$  or  $\epsilon_b$  is the  $b$ -tagging efficiency. Depends also on  $\alpha_k$  - prob. of correctly assigning  $k$ -jets.



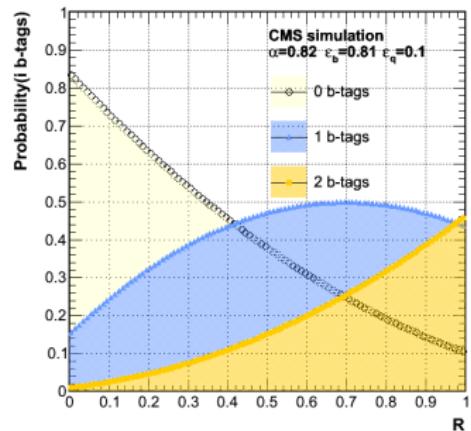
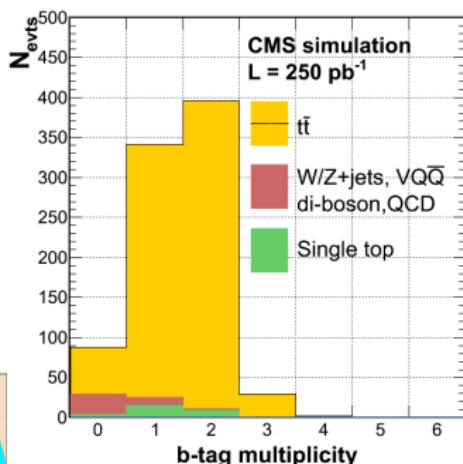
# Dilepton measurement

Introduction  
 $t \rightarrow Wq$   
FCNC  
Conclusion

Introduction  
Dilepton measurement  
Semi-leptonic measurement

## Selection

Selection	Total	$t\bar{t}$ dileptons
Triggered	$(426 \pm 1) \cdot 10^6$	$6251 \pm 25$
$\geq 2$ leptons ( $> 20$ GeV/c)	$(204.7 \pm 0.5) \cdot 10^3$	$2595 \pm 16$
1 e and 1 $\mu$	$2531 \pm 32$	$1344 \pm 12$
$\geq 2$ jets ( $> 30$ GeV)	$1041 \pm 12$	$914 \pm 10$
$\cancel{E}_T \geq 30$ GeV	$884 \pm 10$	$789 \pm 9$
Opp. sign leptons	$867 \pm 10$	$787 \pm 9$



- Diagram above shows  $P_k(R)$ , given correct jet assignment probability  $\alpha = 0.82$  and  $\epsilon_b = 0.81$ ,  $\epsilon_q = 0.1$



# Extracting Information

Introduction  
 $t \rightarrow Wq$   
FCNC  
Conclusion

Introduction  
Dilepton measurement  
Semi-leptonic measurement

Several ways to fit  $R$  (or  $\epsilon_b$ ) from the  $b$ -tag multiplicity:

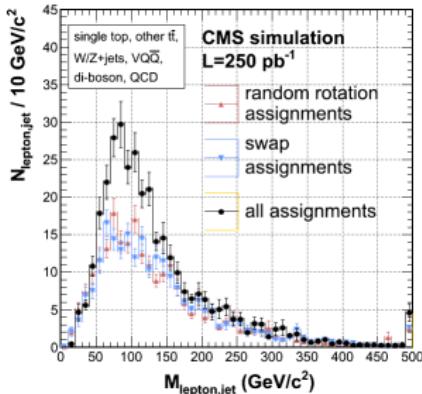
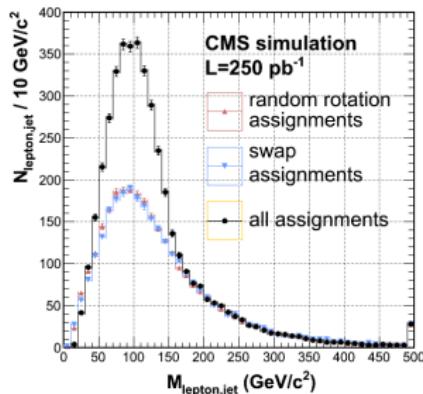
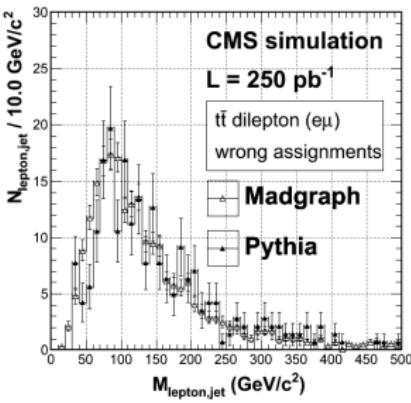
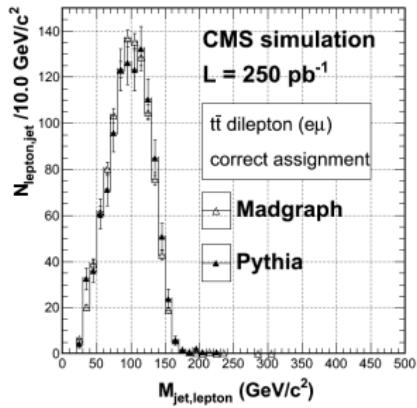
- Fit  $R$  or  $\epsilon_b$  - consistency check
- Choose one bin - check model consistency, select region dominated by particular systematics
- use all selected events inclusively
- Estimate  $\alpha_2$  from data and leave  $\alpha_0$  as a free parameter ( $\alpha_1 = 1 - \alpha_2 - \alpha_0$ ): simultaneously fit  $R$  (or  $\epsilon_b$ ) and the background contribution



# Estimating $\alpha$

Introduction  
 $t \rightarrow Wq$   
 FCNC  
 Conclusion

Introduction  
 Dilepton measurement  
 Semi-leptonic measurement



- $\alpha$  can be estimated using kinematic end point of  $m_{lj}$
- To first order,  $\alpha_{0,1,2}$  can be parametrised as binomial combinations of  $\alpha$ , e.g.  $\alpha_2 = \alpha^2$



# Estimating $\alpha$

Introduction  
 $t \rightarrow Wq$   
FCNC  
Conclusion

Introduction  
Dilepton measurement  
Semi-leptonic measurement

Can get a good estimate of  $\alpha$ :

Method	$N_{mis}^{M>190} / N_{mis}$	$\alpha$
$t\bar{t}$ events from MADGRAPH		
average	$0.21 \pm 0.01$	$0.82 \pm 0.04$
MC truth	$0.20 \pm 0.01$	$0.80 \pm 0.01$
$t\bar{t}$ events from PYTHIA + TAUOLA		
average	$0.21 \pm 0.01$	$0.81 \pm 0.04$
MC truth	$0.23 \pm 0.02$	$0.80 \pm 0.01$

Correspondingly get good estimates of  $\alpha_k$

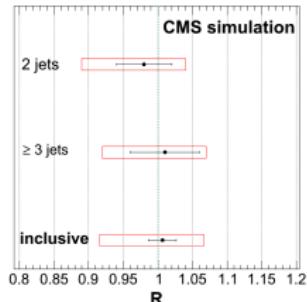
probability	MADGRAPH				PYTHIA + TAUOLA			
	MC truth	Simulated Data	MC truth	Simulated Data	MC truth	Simulated Data	MC truth	Simulated Data
$\alpha_2$	$0.63 \pm 0.02$	$0.67 \pm 0.07$ (stat) $\pm 0.03$ (syst)	$0.63 \pm 0.02$	$0.66 \pm 0.06$ (stat) $\pm 0.02$ (syst)				
$\alpha_1$	$0.31 \pm 0.02$	$0.30 \pm 0.05$ (stat) $\pm 0.02$ (syst)	$0.31 \pm 0.02$	$0.31 \pm 0.05$ (stat) $\pm 0.02$ (syst)				
$\alpha_0$	$0.06 \pm 0.01$	$0.03 \pm 0.01$ (stat) $\pm 0.01$ (syst)	$0.06 \pm 0.01$	$0.04 \pm 0.02$ (stat) $\pm 0.01$ (syst)				



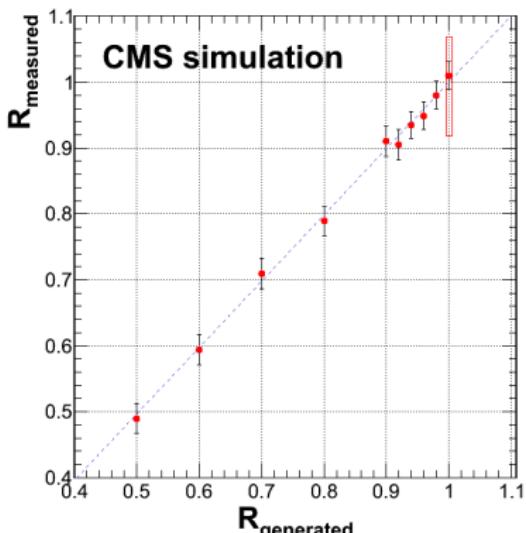
# Results

Introduction  
 $t \rightarrow Wq$   
FCNC  
Conclusion

Introduction  
Dilepton measurement  
Semi-leptonic measurement



- Fit  $R$  with measured  $\alpha$  and with  $\epsilon_b$  as input
- Measurement limited by Systematic uncertainty  $\sim 9\%$
- Dominated by  $b$ -tagging efficiency uncertainty
- This precision is comparable to current Tevatron measurements



# Semi-leptonic measurement

Introduction  
 $t \rightarrow Wq$   
FCNC  
Conclusion

Introduction  
Dilepton measurement  
Semi-leptonic measurement

## Selection

- Trigger (single lepton)
- A single isolated high energy isolated lepton  $p_T > 30 \text{ GeV}$
- At least four selected jets  $p_T > 40 \text{ GeV}$ ,  $|\eta| < 2.4$
- Centrality  $> 0.35$
- $|m_{ij} - m_W| < \sigma(m_W)$
- $\chi^2_{\min} < 4$

$$\chi^2 = \left( \frac{m_{ijk} - m_t}{\sigma(m_{t,\text{Had}})} \right)^2 + \left( \frac{m_{l\nu p} - m_t}{\sigma(m_{t,\text{Lep}})} \right)^2$$

$$\text{Centrality} = \frac{\sum E_T}{\sqrt{(\sum E)^2 - (\sum P_Z)^2}}$$



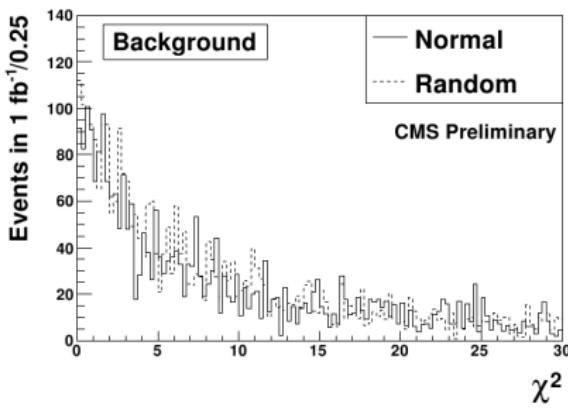
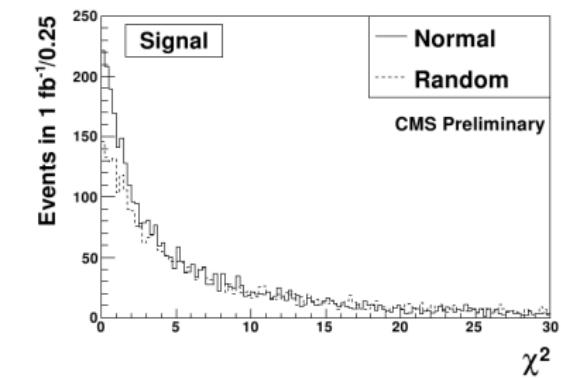
- More background ( $\sim 20\%$ ) than dilepton ( $< 10\%$ )
- Requires background to be subtracted via a data-driven method



# Background Subtraction

Introduction  
 $t \rightarrow Wq$   
FCNC  
Conclusion

Introduction  
Dilepton measurement  
Semi-leptonic measurement



Define two different  $\chi^2$ :

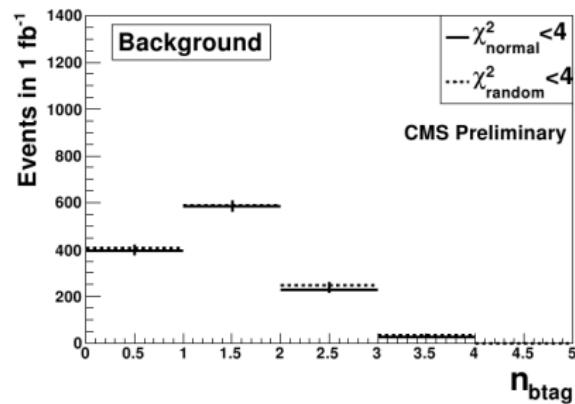
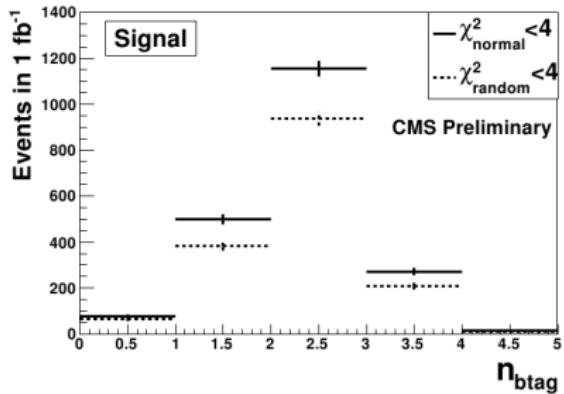
- $\chi^2_{\text{normal}}$  - as defined on the previous slide
- $\chi^2_{\text{random}}$ :
  - Replace highest  $E_T$  jet with new jet (same  $E_T$ ) and random  $\eta$  and  $\phi$
  - calculate  $\chi^2$  as before
  - distribution is similar to  $\chi^2_{\text{normal}}$  for background but different for signal



# Background Subtraction

Introduction  
 $t \rightarrow Wq$   
FCNC  
Conclusion

Introduction  
Dilepton measurement  
Semi-leptonic measurement



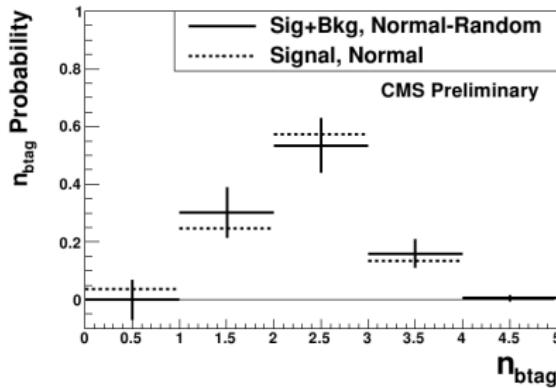
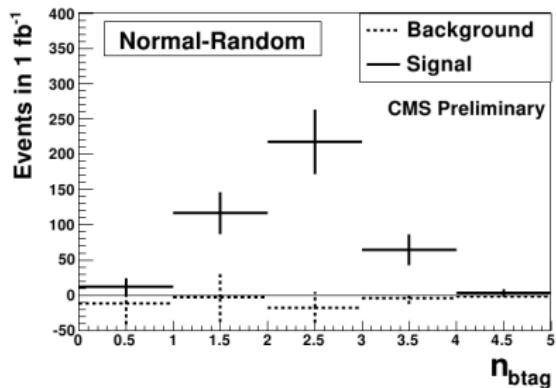
- Produce samples with  $\chi^2 < 4$  cuts on both normal and random  $\chi^2$
- Note that the shapes of the signal and background remain similar
- Subtract the “random” distribution from the “normal” distribution



# Background Subtraction

Introduction  
 $t \rightarrow Wq$   
FCNC  
Conclusion

Introduction  
Dilepton measurement  
Semi-leptonic measurement



- Subtract the “random” distribution from the “normal” distribution
- Background becomes consistent with 0
- Subtracted probability distribution is consistent with the original signal distribution

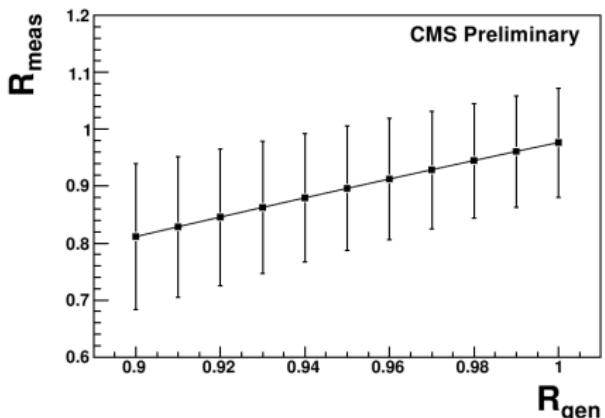


# Results

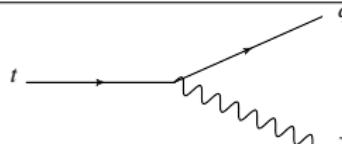
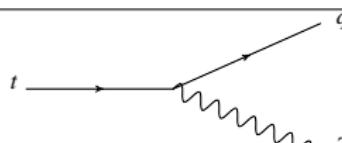
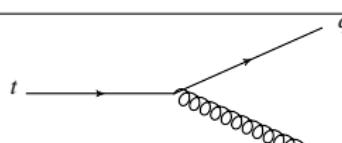
Introduction  
 $t \rightarrow Wq$   
FCNC  
Conclusion

Introduction  
Dilepton measurement  
Semi-leptonic measurement

- $R$  is extracted similarly to the dilepton measurement
- Procedure is more complex because now there are four jets
- Typical uncertainty size 0.12 (stat) and 0.11 (sys)



Flavour-changing neutral current (FCNC) branching ratios in different scenarios<sup>3</sup>:

Decay	SM	Quark Singlet <sup>4</sup>	MSSM	$\mathcal{R}$ SUSY
	$\sim 10^{-14}$	$\sim 10^{-9}$	$\sim 10^{-6}$	$\sim 10^{-6}$
	$\sim 10^{-14}$	$\sim 10^{-4}$	$\sim 10^{-6}$	$\sim 10^{-5}$
	$\sim 10^{-12}$	$\sim 10^{-7}$	$\sim 10^{-5}$	$\sim 10^{-4}$

<sup>3</sup>(from Acta Phys.Polon. B35 (2004) 2695)

<sup>4</sup> $Q = 2/3$ ,  $M_q \geq 300$  GeV



# Experimental Limits

Introduction  
 $t \rightarrow Wq$   
**FCNC**  
Conclusion

Introduction  
 $t \rightarrow qg$   
 $t \rightarrow q\gamma$   
 $t \rightarrow qZ$   
Results

BR	LEP	HERA	Tevatron
$t \rightarrow q\gamma$	2.4%	0.64% ( $t u \gamma$ )	3.2%
$t \rightarrow qZ$	7.8%	49% ( $t u Z$ )	3.7%
$t \rightarrow qg$	17%	13%	$2.0 \times 10^{-4}$ ( $t u g$ ), $3.9 \times 10^{-3}$ ( $t c g$ )

- LEP limits on  $t q \gamma, t q Z$  from single top production searches<sup>5</sup>
- All HERA limits from searches for single top production<sup>6</sup>
- Tevatron limits on  $t q \gamma, t q Z$  from FCNC decays<sup>7</sup>
- Tevatron limits on  $t g q$  from single top production<sup>8</sup>

---

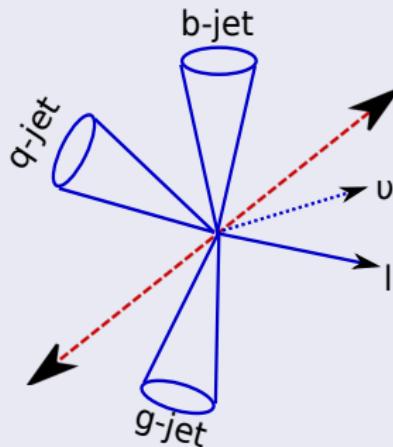
<sup>5</sup>Phys. Lett. B543 173(2002), Phys. Lett. B590 21(2004),  
Phys. Lett. B521 181(2001), Phys. Lett. B549 290(2002), hep-ph/0003033)

<sup>6</sup>Phys. Lett. B559, 153(2003), Phys. Lett. B668 282(2008),  
Phys. Lett. B678, 450(2009)

<sup>7</sup>Phys. Rev. Lett. 80 (1998) 2525

<sup>8</sup>arXiv:1006.3575



$t\bar{t} \rightarrow Wbqg$ 

Signal Eff. : 2.9%  
Main bkg:  $t\bar{t}$ ,  
 $W + \text{jets}$

Signature:

- 3 jets : ( $p_T > 40, 20, 20$  GeV)
- 1 lepton : ( $p_T > 25$  GeV)
- Miss. transv. momentum: ( $\not{p}_T > 20$  GeV)
- No isolated photon: ( $p_T > 15$  GeV)

No  $b$ -tag, get  $p_z^\nu$ , assign  $g, q, b$  by minimising:

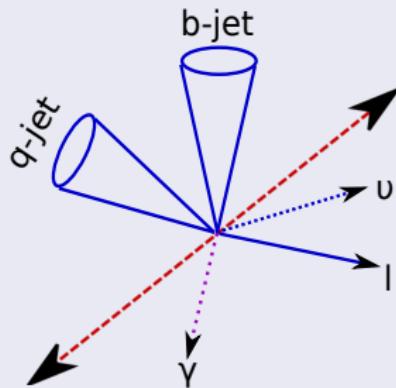
$$\chi^2 = \frac{(m_t - m_{qg})^2}{\sigma_{m_t}^2} + \frac{(m_t - m_{bl\nu})^2}{\sigma_{m_t}^2} + \frac{(m_W - m_{l\nu})^2}{\sigma_{m_W}^2}$$

Extra Selection:

- Visible energy:  $E_{\text{vis}} > 300$  GeV
- $q - g$  mass:  $125 < m_{qg} < 200$  GeV
- gluon-jet  $p_T$ :  $P_T^g > 75$  GeV



$t\bar{t} \rightarrow Wbq\gamma$



Signal Eff. : 7.6%  
 Main bkg:  $t\bar{t}$ ,  
 $W/Z + \text{jets}$

Signature:

- 2 jets : ( $p_T > 20 \text{ GeV}$ )
  - 1 lepton : ( $p_T > 25 \text{ GeV}$ )
  - Miss. transv. momentum: ( $\not{p}_T > 20 \text{ GeV}$ )
  - 1 isolated photon: ( $p_T > 25 \text{ GeV}$ )

No  $b$ -tag, get  $p_z^\nu$ , assign  $q, b$  by minimising:

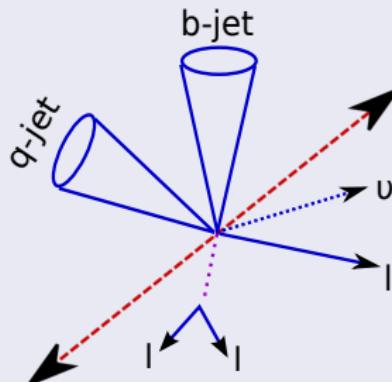
$$\chi^2 = \frac{(m_t - m_{q\gamma})^2}{\sigma_t^2} + \frac{(m_t - m_{bl\nu})^2}{\sigma_t^2} + \frac{(m_W - m_{l\nu})^2}{\sigma_{m_W}^2}$$

#### **Extra Selection:**

- photon  $p_T$ :  $P_T^\gamma > 75 \text{ GeV}$



$t\bar{t} \rightarrow WbqZ$



Signal Eff. : 7.6%  
 Main bkg:  $t\bar{t}$ ,  
 $Z + \text{jets}$

Signature:

- 2 jets : ( $p_T > 30, 20$  GeV)
  - 3 lepton : ( $p_T > 25, 15, 15$  GeV)
  - Miss. transv. momentum: ( $\not{p}_T > 20$  GeV)
  - No isolated photon: ( $p_T > 15$  GeV)

no  $b$ -tag, get  $P_z^\nu$ , assign opposite sign, same flavour leptons to  $Z, W$  by minimising:

$$\chi^2 = \frac{(m_t - m_{I_a I_b q})^2}{\sigma_t^2} + \frac{(m_t - m_{b I_c \nu})^2}{\sigma_t^2} + \frac{(m_W - m_{I_c \nu})^2}{\sigma_W^2} + \frac{(m_Z - m_{I_a I_b})^2}{\sigma_Z^2}$$



# Likelihood Analysis

Introduction  
 $t \rightarrow Wq$   
**FCNC**  
Conclusion

Introduction  
 $t \rightarrow qg$   
 $t \rightarrow q\gamma$   
 $t \rightarrow qZ$   
**Results**

Build likelihood variables:

$$\mathcal{L}_S = \prod_i^n \mathcal{P}_i^{\text{sig}} \text{ and } \mathcal{L}_B = \prod_i^n \mathcal{P}_i^{\text{bkg}}$$

based on probability distribution functions ( $\mathcal{P}$ ) for:

Channel	Variables
$t \rightarrow qg$	$m_{qg}, m_{lq\nu}, m_{qb}, P_T^b, P_T^q, \alpha_{lq},$
$t \rightarrow q\gamma$	$m_{q\gamma}, m_{b\gamma}, p_T^\gamma$
$t \rightarrow qZ$	$m_{qZ}, m_{ll}^{\min}, p_T^\gamma, m_{bZ}, m_{bq}, p_T^q, P_T^{l_3}$

Use the likelihood ratio:

$$L_R = \log_{10} \left( \frac{\mathcal{L}_S}{\mathcal{L}_B} \right)$$

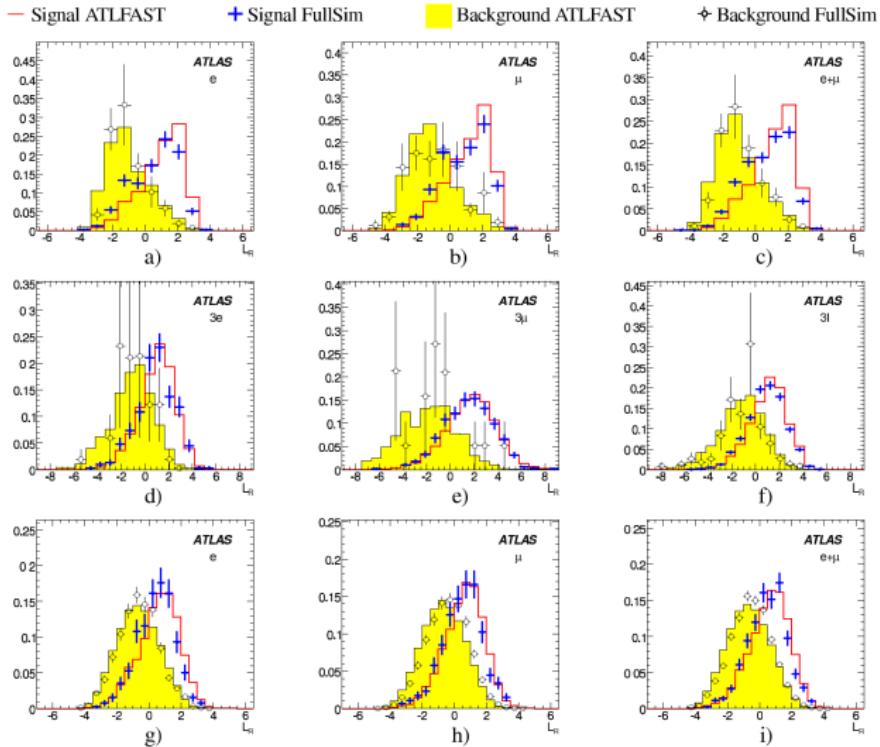
as a discriminant.



# Discriminant distributions

Introduction  
 $t \rightarrow Wq$   
FCNC  
Conclusion

Introduction  
 $t \rightarrow qg$   
 $t \rightarrow q\gamma$   
 $t \rightarrow qZ$   
Results



	$-1\sigma$	Expected	$+1\sigma$
$t\bar{t} \rightarrow bWq\gamma:$			
e	$4.3 \times 10^{-4}$	$1.1 \times 10^{-3}$	$1.9 \times 10^{-3}$
$\mu$	$4.5 \times 10^{-4}$	$8.3 \times 10^{-4}$	$1.3 \times 10^{-3}$
$\ell$	$3.8 \times 10^{-4}$	$6.8 \times 10^{-4}$	$1.0 \times 10^{-3}$
$t\bar{t} \rightarrow bWqZ:$			
$3e$	$5.5 \times 10^{-3}$	$9.4 \times 10^{-3}$	$1.4 \times 10^{-2}$
$3\mu$	$2.4 \times 10^{-3}$	$4.2 \times 10^{-3}$	$6.4 \times 10^{-3}$
$3\ell$	$1.9 \times 10^{-3}$	$2.8 \times 10^{-3}$	$4.2 \times 10^{-3}$
$t\bar{t} \rightarrow bWqg:$			
e	$1.3 \times 10^{-2}$	$2.1 \times 10^{-2}$	$3.0 \times 10^{-2}$
$\mu$	$1.0 \times 10^{-2}$	$1.7 \times 10^{-2}$	$2.4 \times 10^{-2}$
$\ell$	$7.2 \times 10^{-3}$	$1.2 \times 10^{-2}$	$1.8 \times 10^{-2}$



Limits obtained using the modified-frequentist likelihood method (95% C.L, in absence of any signal)

Systematic uncertainties:

- $t \rightarrow qg \sim 27\%$
- $t \rightarrow q\gamma \sim 32\%$
- $t \rightarrow qZ \sim 27\%$

mainly ( $m_t$ , ISR/FSR, pile-up,  $\sigma_{bkg}$ , generator effects)



# Sensitivity Comparison

Introduction  
 $t \rightarrow Wq$   
**FCNC**  
 Conclusion

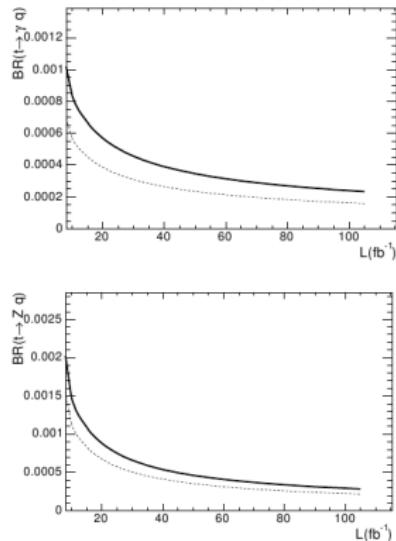
ATLAS 1  $\text{fb}^{-1}$

	$-1\sigma$	Expected	$+1\sigma$
$t\bar{t} \rightarrow bWq\gamma:$			
e	$4.3 \times 10^{-4}$	$1.1 \times 10^{-3}$	$1.9 \times 10^{-3}$
$\mu$	$4.5 \times 10^{-4}$	$8.3 \times 10^{-4}$	$1.3 \times 10^{-3}$
$\ell$	$3.8 \times 10^{-4}$	$6.8 \times 10^{-4}$	$1.0 \times 10^{-3}$
$t\bar{t} \rightarrow bWqZ:$			
3e	$5.5 \times 10^{-3}$	$9.4 \times 10^{-3}$	$1.4 \times 10^{-2}$
$3\mu$	$2.4 \times 10^{-3}$	$4.2 \times 10^{-3}$	$6.4 \times 10^{-3}$
$3\ell$	$1.9 \times 10^{-3}$	$2.8 \times 10^{-3}$	$4.2 \times 10^{-3}$
$t\bar{t} \rightarrow bWqg:$			
e	$1.3 \times 10^{-2}$	$2.1 \times 10^{-2}$	$3.0 \times 10^{-2}$
$\mu$	$1.0 \times 10^{-2}$	$1.7 \times 10^{-2}$	$2.4 \times 10^{-2}$
$\ell$	$7.2 \times 10^{-3}$	$1.2 \times 10^{-2}$	$1.8 \times 10^{-2}$

N.B. A 95% C.L. limit in absence of signal unlike CMS (5 $\sigma$  discovery).

Introduction  
 $t \rightarrow q\gamma$   
 $t \rightarrow qZ$   
 Results

CMS 5 $\sigma$  discovery reach Vs  $\mathcal{L}$



Channel	BR 5 $\sigma$ ( $10 \text{ fb}^{-1}$ )
$t \rightarrow q\gamma$	$8.4 \times 10^{-4}$
$t \rightarrow qZ$	$1.5 \times 10^{-3}$

CERN-LHCC-2006-021



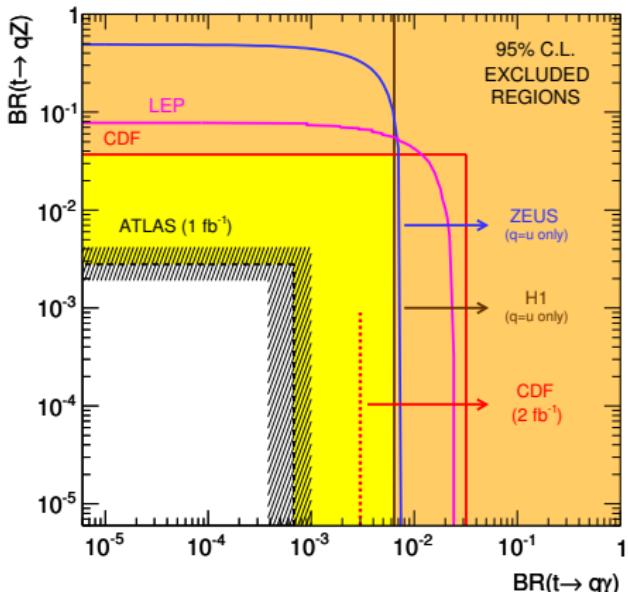
# Limits

Introduction  
 $t \rightarrow Wq$   
**FCNC**  
Conclusion

Introduction  
 $t \rightarrow qg$   
 $t \rightarrow q\gamma$   
 $t \rightarrow qZ$   
Results

- With  $1 \text{ fb}^{-1}$  @  $\sqrt{s} = 14 \text{ fb}^{-1}$ , expected limits from ATLAS on  $t \rightarrow q\gamma$  and  $t \rightarrow qZ$  comfortably outstrip:
  - Existing and prospective limits from the Tevatron
  - Existing limits from single top production at LEP
  - Existing and prospective limits from HERA

More details: [arXiv:0901.0512](https://arxiv.org/abs/0901.0512)



- Feasibility studies show good potential at the LHC for rare top decay studies
- For  $R = (t \rightarrow Wb)/(t \rightarrow Wq)$ :
  - With  $\mathcal{O}(250 \text{ pb}^{-1})$  (@10 TeV) competitive measurements to those at Tevatron
  - From top cross section would expect something similar for  $\mathcal{O}(500 \text{ pb}^{-1})$  @7 TeV
- For FCNC:
  - Excellent prospects for sensitivity beyond current limits
    - Far better sensitivity for  $1 \text{ fb}^{-1}$  @14 TeV
    - Would expect that sensitivity is still better for  $1 \text{ fb}^{-1}$  @7 TeV from the top cross section.



FCNC  
Systematics

## Back Up

FCNC Systematics

Source	t → qγ			t → qZ			t → qg		
	e	μ	ℓ	3e	3μ	3ℓ	e	μ	ℓ
Jet energy calibration	1%	2%	2%	3%	2%	5%	4%	4%	4%
Luminosity	9%	8%	10%	3%	2%	6%	10%	8%	10%
Top quark mass	7%	7%	6%	6%	4%	12%	7%	5%	5%
Backgrounds $\sigma$	6%	10%	7%	4%	7%	12%	17%	16%	15%
ISR/FSR	21%	18%	17%	6%	29%	7%	3%	7%	9%
Pile-up	37%	21%	22%	30%	14%	0%	8%	10%	13%
Generator	34%	18%	4%	4%	14%	14%	5%	0%	4%
$\chi^2$	5%	0%	4%	2%	5%	7%	3%	7%	9%
Total	56%	36%	32%	32%	36%	25%	24%	24%	27%

